3

Observational Capabilities and Needs

In the event of C/B/N releases, observations will play a key role in tracking the agent and anticipating its spread, its dilution rate, and the projected exposure of the population. The unpredictability of such events dictates the need for instruments to be in place before a release occurs, mobile instruments that can be rapidly deployed to the site of the events, and longer-term deployable instruments to determine the total impact and indicate when affected areas are safe again.

It first is necessary to locate the plume and determine its composition, if possible. Identifying the composition will require knowledge of the "background" levels of agents of interest to prevent false alarms or misidentification of plume boundaries. Forecasting the plume direction requires knowledge of the wind field, which can be influenced strongly by local flows. Some measure of turbulence intensity is needed to determine how fast the plume will spread both vertically and horizontally. The amount of C/B/N agent that will settle to the surface is determined by the turbulence level and the composition of the plume in the case of dry deposition, and by the composition of the plume and scavenging by clouds and precipitation in the case of wet deposition. If the source of a release remains unknown after the events, downwind observations in combination with trajectory models are needed to back-calculate the source location (and possibly even the source strength). For instance, in the Chernobyl event, hemispheric-scale observations were used to detect the problems and identify its source. In the case of a terrorist attack, such observations also may play a valuable role in ongoing criminal investigations of the dispersal methods and individuals or groups involved.

The complementary role of observations and models will change through the course of a C/B/N release. Initial response will likely rely entirely on direct observations. Just after the event, forecasters (that is, those employing observations and modeling tools to make dispersion predictions) will rely on simple extrapolation of local data. Eventually, the forecaster will blend numerical models and nowcasting[1] techniques that draw on the relevant data. On time scales of hours to days or weeks, numerical models will be used to a much greater extent, although observational data from synoptic-scale

[1] Nowcasting refers to short-term weather forecasts, generally out to six hours or less.

networks will have to be assimilated continuously into the models. While the general improvement of synoptic networks and weather forecasts is important, the committee's emphasis is on special needs for tracking and predicting C/B/N plumes on a local scale in the first hours after release. The emphasis eventually may shift to regional and global models, but the observations required for model forecasts on these scales are beyond the scope of this report.

PLUME IDENTIFICATION

Identifying and following a C/B/N plume is critical both for real-time response efforts and for model nowcasting and forecasting. The first detection of a C/B/N agent could be from a directly observed plume, from fixed sensor instruments (Box 3.1), or from sickened humans or animals. Once a C/B/N event has been identified, there are a number of technologies that could be employed for three-dimensional sampling and tracking of a plume (Appendix C), although there are limitations associated with each. Scanning lidars, which use optical radiation much like radars use microwave radiation, can be used to sense aerosols and some trace gases out to 10–20 km (Plate 1) (Banta et al., 1999; Darby et al., 2002), although complex terrain and urban environments can limit the line of sight for such instruments. Furthermore, lidars are expensive and currently only available for civilian use in a research context. Microwave radars can identify and follow some plumes, depending on their composition.

There are a number of mobile platforms that can be used to deploy such instruments. For instance, boundary layer profilers or small radars can be readily mobilized on trucks or trailers. Helicopters can be used to lower tethered sensor pods into affected regions[2] as long as care is taken not to induce turbulence and considerably stir up the plume. Unmanned aerial vehicles (UAVs) can carry sensors that directly sample plume composition into regions not easily accessible to ground-based lidars or radars, such as urban canyons. To be effective however, these types of mobile platforms would have to be readily available for immediate deployment at the site of the emergency. For instance, if the UAV release point is far from the C/B/N impact region, the time required for deployment may limit the usefulness of this approach. In the absence of high clouds, satellites can track visible plumes. Gases have characteristic signatures in the infrared, so new satellites sensing the infrared spectrum at higher wavelength and spatial resolution (Mecikalski et al., 2002) will have increased capability for possibly identifying some plume constituents.

WIND—LOCAL FLOWS

Wind measurements are needed to track a near-surface C/B/N release in real time and to provide input for dispersion models, numerical weather prediction (NWP) models,

[2] Helicopters that operate routinely in urban areas for purposes such as traffic reporting have frequently been used as platforms for other types of observational equipment (e.g., such as that used in air pollution studies).

BOX 3.1
C/B/N Sensors

C/B/N sensors are an integral part of any system for tracking and predicting the dispersion of hazardous agents. There has recently been a concerted effort to accelerate the development and deployment of these sensors, and it is likely that C/B/N sensor data will become increasingly available. Assimilation of these data—both for model development and real-time operations—is a key new capability that will help optimize dispersion predictions. The National Academies' Board on Chemical Sciences and Technology recently held a workshop that included some discussion of C/B/N sensor technologies. Below is a summary of some points raised at that workshop (NRC, 2002a).

Because the amount of agent used in an attack can be relatively small, real-time sample collection, concentration, and analysis all are crucial issues for detection of C/B/N agents. There is a great deal of ongoing research to develop specific, sensitive, fast, and portable sensors. For example, new microfluidics technologies to accurately control the flow of liquids on a small (millimeter-scale) device have been key to the development of low-cost, portable packages used by first responders and emergency medical personnel to rapidly analyze small samples. To extend miniaturization to the sampling and concentrating of airborne particles, advances are needed in flow and handling of small volumes of gases.

Analytical techniques for the detection of some chemical and explosive agents are well established, including mass spectrometry and ion mobility spectrometry. However, current methods need to be improved and expanded to allow detection of many other potentially important chemical agents. Some promising technological developments include:

- fiber optic-based sensors that provide rapid response to a variety of chemicals at trace concentrations;
- flow injection analysis on a microelectromechanical system platform that provides high sensitivity and selectivity within hundreds of seconds from a small sample volume; and
- micromachined gas chromatography sensors that aid in real-time chemical sensing of toxic gases.

Some key challenges in this field include improving detector sensitivity and specificity and reducing the power drain so that smaller-size batteries can be used. Advances in microelectronics that have enabled the fabrication of compact, low-power devices and new miniaturization techniques, nanofabrication tools, and fundamental materials chemistry should allow significant advances to be made in the coming years.

There also have been a number of promising advances in sensors for biological agents, for example:

- Developments in using mass spectrometric techniques to identify large biomolecules likely will prove important in identifying biological warfare agents.
- Recent work has included concentrating and identifying bacterial pathogens such as anthrax spores based on protein biomarkers.
- Components of biological systems, such as an antibody or a biomimetic membrane, have been incorporated into sensors for biological or chemical toxins.

The most significant challenges in this area are to develop efficient approaches to collect, separate, concentrate, and process samples and to develop miniature devices that work under ambient conditions. General research into the biochemistry of agents and the rapid identification of agent pathogenicity is needed for developing the ability to respond to new threats such as artificially bioengineered agents.

Knowledge of background levels of radioactivity, hazardous chemical, and spores and other bioagents is necessary to isolate real events from false alarms. Air pollution monitoring data provide information about the background concentrations of some hazardous chemicals, and the background radioactivity may be known in some areas with a history of mining or processing of radioactive materials. However, there generally is no ambient monitoring for most C/B/N agents of concern[3], and for many important hazardous agents, techniques for determining background levels do not even exist. It is particularly difficult to distinguish toxic biological agents from the harmless biological compounds ubiquitous in our environment or from naturally occurring toxic biological agents.

Within the scientific research community, there is a general lack of knowledge about many of the characteristics of pathogenic or toxic agents. Innovations in this area could be encouraged by making available to researchers an extensive database on the properties of pathogens. A logical home for such a database might be the Chemical and Biological Information Analysis Center at Aberdeen Proving Ground, where extensive information about chemical and biological agents is maintained.

and hybrid (dispersion-NWP) models. Near-surface and low-level winds (i.e., surface and boundary layer winds during daytime; winds within the lowest few hundred meters at nighttime) are most critical in the first hours after a C/B/N release. Local terrain can cause strong spatial variations in wind speed and direction, creating local flows that are, in turn, disrupted by the presence of buildings. Local flows (e.g., mountain-valley winds, land and sea breezes, horizontal eddies caused by deflection of the wind by terrain) lead to large deviations from what would be expected for flat, uniform terrain. While some local flows can be easily observed, flows such as the Catalina Eddy in the Los Angeles area (Bosart, 1983) and the Denver Cyclone (Wilczak and Glendenning, 1988) were

[3] However, there was a recent announcement that air quality monitoring stations around the country will be augmented with sensors to monitor for anthrax, smallpox, and other deadly biological agents (Miller, 2003).

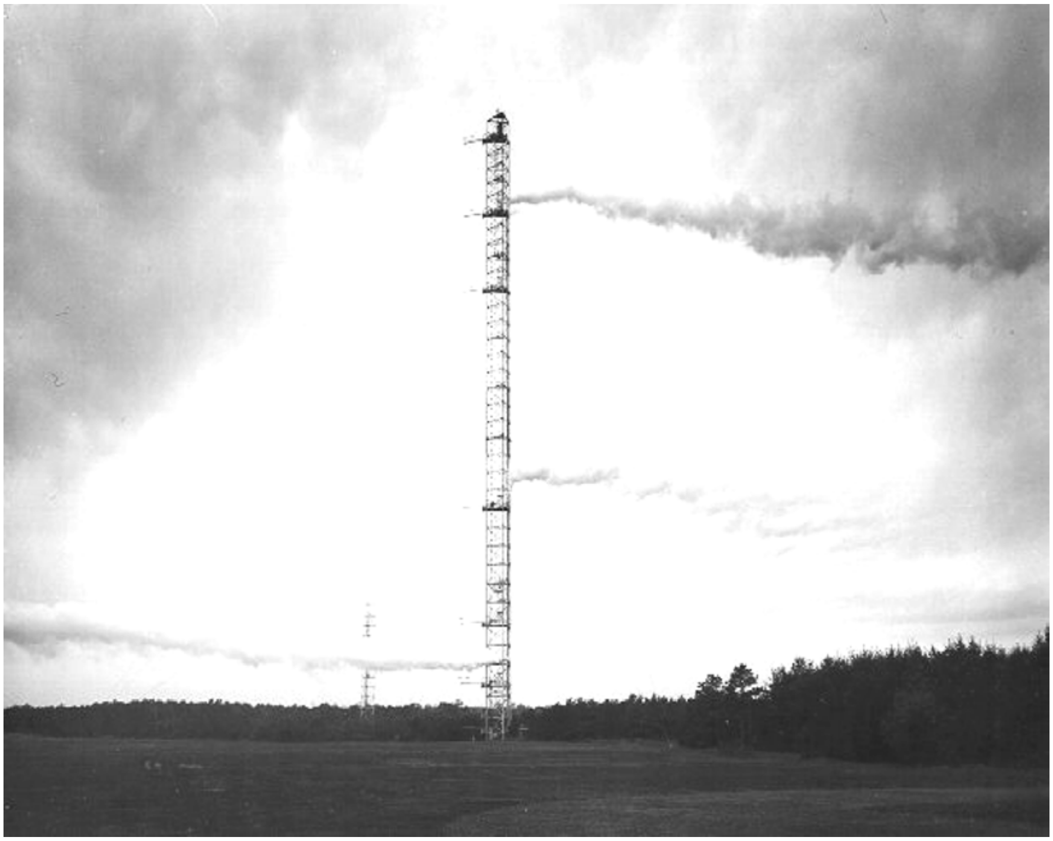

FIGURE 3.1 This 1973 photograph showing a "smoke run" at Brookhaven National Laboratory graphically illustrates the point that wind currents can move independently (and even in opposite directions) in separate layers of the lower atmosphere. The flatness of the smoke plumes suggests little turbulence, thus little vertical mixing in this case. (SOURCE: Courtesy of Brookhaven National Laboratory).

unknown until dense meteorological observations were taken. Such circulations are of the order of 100 km across or less—too small to be well observed by standard surface weather observing networks. Other local- to mesoscale (roughly 10–100 km) circulations can develop independent of the local terrain. Those associated with convective storms are readily identified and closely watched, but we are only dimly aware of other less apparent circulations that persist after a storm has died or that develop in response to subtle differences in land cover or soil moisture. Such circulations will need to be measured on a routine basis.

Local flows can carry C/B/N plumes in unexpected directions; for example, in some conditions a plume can stagnate or suddenly reverse direction. As illustrated in Figure 3.1, flows can vary dramatically depending upon the height above ground (Appendix C). Thus, forecasters must make an effort to understand the behavior of local flows in their areas. Such advance work enables optimization of measurements and trains the forecaster to interpret measurements and model output correctly. More needs to be known about how local flows develop in geographical areas with subtle variations in terrain or land use. More, too, needs to be known about how local terrain or urbanization affects frontal passages, mesoscale convective systems such as squall lines, and other weather phenomena (Appendix F). The same reasoning applies to the application of forecast models to local flows—good forecasters understand the strengths, weaknesses, and biases of the numerical weather forecast models they use on a daily basis. However, these models typically are applied to larger scales than those of interest in the context of a C/B/N release, and some forecasters have little experience with the behavior of the localized models needed to follow a C/B/N release during the first several hours. Forecasters in highly critical areas should monitor local flows routinely and compare this behavior to the prediction from mesoscale models to develop experience in forecasting local flows.

Tracking a C/B/N event in real time requires instrument arrays that can document the local flows determined by terrain or buildings. Low-level upstream winds may be useful for initiating numerical simulation of the airflow, particularly in areas with complex terrain. After several hours to days, depending on the weather and the extent of the release, winds at higher altitudes can become important in tracking and forecasting the plume dispersion to determine the potential risks faced by downwind populations. Mesoscale circulations can be readily detected by dense networks of surface weather observation towers that are typically instrumented to measure wind direction and speed, pressure, temperature, and humidity. To resolve a circulation, the station spacing has to be much smaller than the circulation scale—at least three observation sites across the circulation are required to detect it, and at least six are needed to resolve the circulation reasonably well along one direction. Circulations in "clear air" also are visible from Doppler radar through the presence of insects or strong humidity and temperature fluctuations, the latter of which make air visible to the radar by modifying the atmosphere's refractive index.

The U.S. meteorological observation network—including federal, state, local, private, and research networks—can meet a significant fraction of this daunting need. The Joint Office of Scientific Support at the University Corporation for Atmospheric Research maintains a database of available observational networks as part of its mission to support field programs (see http://www.joss.ucar.edu/gapp/networks). Also, the University of Utah has teamed with the National Weather Service (NWS), other government agencies, and the private sector to collect data from surface networks throughout the western United States for purposes of research, education, and operational support (see http://www.met.utah.edu/jhorel/html/mesonet/). There are dozens of tightly packed surface-tower arrays or single towers around the country run for monitoring air pollution or highway conditions, storm forecasting, research, K-12 education, or television weather programs. One such network, the Oklahoma Mesonet (Brock et al., 1995), is described in Box 3.2. Additionally, about a dozen universities operate buoys that provide environmental information offshore (Mesonet, 2002). With the increasing number of regions establishing mesonet systems, it would be useful to have one central focal point for coordinating the real-time acquisition and quality assurance of data from these networks. Furthermore, the development of "universal" software would allow easier access to and greater usability of these data.

BOX 3.2
Example of a Multiuse Observational Network

The Oklahoma Mesonet (http://www.mesonet.ou.edu/) is a world-class observational network designed by scientists at the University of Oklahoma and Oklahoma State University. It includes 114 environmental monitoring stations distributed across the state. Each site includes a set of instruments, located on or near a 10-m tower, that measure parameters such as air temperature, relative humidity, wind speed and direction, barometric pressure, rainfall, and solar radiation. The observations are transmitted to a central facility every 15 minutes, 24 hours per day, year-round. The Oklahoma Climatological Survey receives the observations, verifies the quality of the data, and provides the data to Mesonet customers. It only takes 10 to 20 minutes from the time the measurements are acquired until they become available.

The Mesonet data are applied for a wide array of uses, including weather forecasting, education and scientific research, and planning for agriculture, energy supply, and transportation. In addition, the network already is being used by public safety agencies for tracking hazardous material release incidents, as described in Morris et al., (2001) and as highlighted in the following quote: “Mesonet is without a doubt among the most important data sets we use at the National Weather Service Forecast Office. In addition to routine forecast and warning operations, the Mesonet is invaluable for handling various disaster support situations including wildfires, chemical spills, and catastrophes like the Oklahoma City Murrah Building bombing” (David Andra, NWS Forecast Office, Norman, Oklahoma).

The NWS, the Federal Aviation Administration, and the military operate a national network of Weather Surveillance Radar-1988 Doppler (WSR-88D) radars (see NRC, 1995; Figure C.1), and radars operated by television stations may be used to provide additional coverage with the permission of the stations. For low-level scans, radar clear-air wind field coverage at the surface is limited by Earth’s curvature to a maximum distance of about 50 km (Plate 2). The current pre-programmed radar scans might not be optimum for determining the low-level wind field with the detail needed to follow a C/B/N release. However, one of the possible enhancements to the radar network (NRC, 2002b) is to supplement the current WSR-88D network with subnetworks of smaller, less powerful, and less expensive short-wavelength (3- and 5-cm) radars to provide more low-level coverage. New scan designs for C/B/N responses also should be considered.

The National Oceanic and Atmospheric Administration (NOAA) operates a network of vertically pointing 400-MHz band radar wind profilers across the central part of the United States (Martner et al., 1993), which provides winds at heights from 500 m to about 16 km, but the lack of data at lower levels and the relatively coarse vertical resolution limit the usefulness of these profilers for near-surface applications. There are, however, several 900-MHz band boundary layer radar wind profiler networks being used for research in Oklahoma, Kansas, Texas, California, and elsewhere. Some are combined with Doppler sodars to obtain winds down to about 30 m off the surface. Radar wind profilers with radio acoustic sounding systems (RASS) provide estimates of the temperature profiles through slightly shallower depths than where winds are measured. Aircraft winds are available from the surface to jet cruising altitude through the Meteorological Data Collection and Reporting System (MDCRS; Moninger et al., 2003).

Once a C/B/N release occurs, nearby wind sensors (as well as simple “intuitive” indicators such as flags and the trajectories of visible smoke plumes) will be used to help locate the site and spread of the release. Data from the fixed observational arrays discussed above will be useful, but additional observing systems may need to be mobilized to cover some areas affected by a C/B/N release. If the release is in a city with tall buildings, estimates of the wind in urban canyons will be urgently needed, since model winds will likely be woefully inadequate. Video surveillance cameras, or “web-cams,” could provide information on the motion of visible plumes. Inexpensive optical cross-wind sensors could be used to sense winds in selected urban canyons. These instruments measure the average wind component transverse to their optical axis usually to a distance of 200 m to 1 km. They are ideally suited to be deployed between buildings, and they give the down-street flow, possibly at multiple stories to estimate vertical wind structure. By slanting the path along the street, estimates of the average wind vector can be determined.

Mobile sensors could include scanning Doppler lidars or radars and UAVs. These platforms complement one another, since lidars can “see” aerosols in relatively clear air, even if there are not enough scatterers for the radars to detect a signal. Although lidars may not be useful in the presence of clouds and rain, radars can derive winds from insect scatterers, precipitation, and possibly the plume itself. Radar and lidar are limited to line-of-sight data, but in some contexts, UAVs may be able to fill in wind field observations between buildings. Mobile Doppler wind profilers could provide data between 150 m and 1–2 km above the ground. Depending on the instrument type and application, mobile sensors could be carried on trucks, aircraft, helicopters, or boats. These mobile instruments will be needed most urgently in the first minutes to hours after a release, hence, rapid access is critical. Such instruments must be located close to threatened areas and be available for immediate deployment, which may be feasible only in a few select locations.

DEPTH AND INTENSITY OF TURBULENT LAYERS

The depth of the turbulent layer near the ground and the intensity of the turbulence (and hence mixing) also are in the minimum data set necessary to estimate the transport and dispersion of a C/B/N release, to determine how the plume will spread and mix vertically as well as horizontally (i.e., three-dimensionally) (Appendix C).

The heights and depths of turbulent layers are shown clearly in reflectivity profiles from 900-MHz band radar wind profilers at altitude ranges from 150 meters to a few kilometers (Plate 3). If collocated with radar wind profilers, the RASS provides temperature profiles with the same height restrictions, although its use may be compromised by its noisiness. Sodars can provide information similar to that of radar wind profilers near the surface. Doppler lidars can detect layers of turbulent mixing vertically up to 10–15 km (Plate 4a) as well as horizontally to a distance of 10–20 km (Plate 4b and Plate 5) (Rothermal et al., 1998; Banta et al., 1999; Darby et al., 2002). If there is an airport nearby, MDCRS temperature profiles from commercial air carriers can be used to identify layers where mixing is likely.

For a C/B/N release occurring a few hundred meters above the surface (for instance, a release from a crop duster), the urgent question is how quickly the hazardous material will mix or settle to the surface. During the daytime, there often is strong turbulence throughout the lowest few hundred meters, which would quickly mix the material to the ground. However, when there is warm air moving over a cold surface or when cloudy skies prevent strong heating of the ground, there may be little mixing. The stable warm-over-cold air temperature layering that often occurs at night can isolate the surface from such releases, but breaking waves or surges of cold air can initiate mixing between the turbulent layer and the surface, or the wind change between the layers can increase enough to promote mixing (Box 3.3). Surges of cool air are visible in surface-station arrays, and breaking waves are observable using scanning lidars. Temperature and wind profiles can be determined from MDCRS data, UAV data, RASS data, or special radiosonde soundings. As illustrated by Figure 3.1, vertical profile information is critical, since a release at the surface may have a vastly different outcome than a release occurring at various heights above the surface.

DEPOSITION AND DEGRADATION

A C/B/N release must be viewed as more than just an atmospheric hazard, since the hazardous agents eventually will be deposited from the atmosphere onto surfaces such as buildings, soil and vegetation, and aquatic systems. Deposition patterns and the resulting impacts will depend heavily upon the contaminants' atmospheric residence time (which could vary from minutes to weeks, depending on particle size and other physical properties of the agent) and environmental viability (that is, how rapidly the agent's potency diminishes after exposure to ambient conditions). The deposition process occurs through one of several possible mechanisms including dry deposition, wet deposition (rain or fog), or gas-phase reactions with various surfaces.

Dry deposition of a hazardous agent shortly after release time can be estimated from plume location, concentration, and the turbulence level. Such agents may pose a "secondary hazard" if they are returned to the atmosphere or water supply by wind, rain, or fires and, in some cases, persistent agents may eventually propagate through ecological systems and the food chain. Appropriate sensors can be deployed to track these latent sources of potential harm, although tracking residual agents sequestered in isolated areas or adsorbed on various materials may involve a challenging assay process.

Wet deposition of a hazardous agent occurs when precipitation containing the agent falls to the surface (vertical deposition) or when cloud droplets containing the agent intercept the surface or vegetation on hill or mountain slopes (horizontal deposition). Moisture also plays a key role in the degradation of some hazardous agents; for example, degradation of nerve and mustard agents occurs via hydrolysis by aqueous aerosols and

BOX 3.3
Daytime and Nighttime Mixing Patterns

When a toxic release occurs, mixing and dispersion patterns will differ significantly depending on such factors as the time of day the release occurs and the weather conditions at the time. Two extreme examples illustrate these effects.

During a summer day with abundant sunshine, the sun heats the ground and, indirectly, heats the air close to the ground. This warmed air rises, cooling and entraining cooler air as it does so (e.g., Plate 4a). The buoyant plumes will continue to rise and cool until they are cooler than the air around them, at which point further upward motion is cut off. Air from the surrounding area flows in to replace the buoyant plumes, and this leads to efficient vertical mixing in the lower atmosphere. The layer at which this turbulent mixing occurs is called the atmospheric boundary layer. In this type of daytime scenario, cloud cover tends to retard heating and acts to reduce thermal mixing.

During a clear winter night, the ground radiates heat energy to the surrounding atmosphere (e.g., Plate 4b). The air near the ground becomes cold relative to the air above it, which leaves the coldest air "trapped" near the ground. Turbulence and mixing are suppressed by this thermal stratification. Under these conditions, the atmospheric boundary layer commonly is less then 100 m deep and can occasionally be as shallow as a few meters. Sometimes the air is more turbulent a few hundred meters above the ground than at the surface (e.g., when the wind blows over the top of a stable lower layer); thus, important mixing can take place above the boundary layer. In a nighttime situation, cloud cover tends to suppress radiative cooling and thus mitigate the cold air trapping near the surface. It is important, then, to monitor not only the height of the boundary layer, but also the temperature and wind throughout the lower few hundred meters.

damp surfaces. Thus, it becomes important to monitor clouds, precipitation, dew points, and soil moisture along the track of the C/B/N plume. Clouds are routinely monitored from meteorological, environmental, and other satellites. The Doppler radar network does an excellent job of documenting precipitating storms over the continental United States, but does only a fair job of estimating precipitation amount. In the future, precipitation data from the Global Precipitation Mission satellites (Shepherd and Mehta, 2002; Shepherd and Smith, 2002) and stream-gauge data will aid in estimating precipitation. Progress also is being made in running mesoscale models using assimilated radar data, providing another avenue for future improved estimates. Satellite views of the low clouds associated with horizontal deposition may be obscured by higher clouds, so forecasters and emergency managers will have to rely on models and wind field observations to project where the plume will intercept hills or mountains. Following deposition, hydrological and ecological models and observations may be required to provide information about subsequent dispersal of the hazardous agents through the environment.

KEY FINDINGS AND RECOMMENDATIONS

The most basic observations required for tracking and predicting the dispersion of a hazardous agent include identification of the plume; characterization of low-level winds (to follow the plume trajectory); characterization of the depth and intensity of the turbulent layers through which the plume moves (to estimate plume spread); and identification of areas of potential agent degradation and dry or wet deposition. Table 3.1 summarizes the observations and instruments most useful for a response to a C/B/N release.

The current array of surface observational systems needs to be better used and enhanced. Many surface stations are poorly exposed and have limited instrument quality control, and instrument locations are not necessarily optimal for model initialization or identification of local flows. Furthermore, it often is difficult to obtain the data from multiple observational arrays, especially in real time. **A comprehensive survey of the capabilities and limitations of existing observational networks should be conducted, followed by action to improve these networks and access to them, especially around more vulnerable areas**.

Doppler radar systems can be useful for estimating boundary layer winds, monitoring precipitation, and tracking some C/B/N plumes. The National Research Council (2002b) recommended evaluating the potential for supplementing current Doppler radar network with subnetworks of short-range, short-wavelength radars. This would enable better estimates and coverage of low-level winds, increase the likelihood of detecting C/B/N plumes, and improve precipitation (and hence wet deposition) estimates. **The committee supports this recommendation and further recommends that the design and data collection strategy of this radar network be optimized to include providing information for supporting response to a C/B/N release.**

Radar wind and radio acoustic sounding system profilers, which measure variations of the horizontal wind and temperature, respectively, with height and enable identification of turbulent layers, provide important information for response to C/B/N attacks and are relatively inexpensive and easy to maintain**. Wind and temperature profilers should become an integral part of regional and local fixed-observational networks.**

Mobile observational platforms can provide valuable information and fulfill multiple needs in the first minutes to hours after a hazardous release. Unmanned aerial vehicles can be used to measure wind and temperature profiles and to characterize turbulence where other platforms cannot easily reach. Mobile lidars and radars can, in some contexts, be used for plume tracking and wind field characterization. However, civilian instruments currently are available only for research use. **There should be continued development of portable scanning lidars and radars on airborne and**

TABLE 3.1 Observations and instruments useful for response to a C/B/N release. Details on some of the systems appear in Appendix C.

Observations	Reason	Instruments	Coverage	Needed Enhancements
Plume location	Determine or project affected population	Scanning lidar	*Vert:* 0 to 1-2 km *Horiz:* up to 10-20 km	Affordable, eye-safe
		Scanning radar (clear air)	*Vert:* 0 to 1-2 km *Horiz:* 10-50 km, depend on plume	More radars to increase low-level coverage (as proposed in NRC, 2002b); special scans and data processing to obtain low-level wind field
		Satellite visible or IR	Visible daytime only	
		UAV	Where sent	Available quickly to critical locations
Plume composition	Estimate exposure	Scanning lidar (fixed or mobile)	*Vert:* 0 to 1-2 km *Horiz:* up to 10-20 km	Affordable, eye-safe
		Satellite IR	N/A	High spatial and wavelength resolution. Several such satellites are planned, including the GOES[a]-Advanced Baseline Imager and Advanced Baseline Sounder (planned launch 2012), and polar-orbiting sites (planned launch 2007-2008), which will have higher horizontal resolution. (Mecikalski et al. 2002)
		In situ sensing from UAV or sensor pod attached to helicopter	Where sent	Available quickly to critical locations
Low-level winds	Document horizontal transport by local flows; model input	Multiple surface meteorological-tower arrays	2-10 m	*Present arrays:* useful arrays identified, improved exposure and quality control, reliable data transmission to users *Additional instruments:* add or move present stations for detecting local flows in critical areas
		Scanning lidars	*Vert:* 0.1-1 or 2 km *Horiz:* ~0.1km to 10-50 km	*Present arrays:* flexibility to do needed scans to follow C/B/N plume *Future:* greater low-level coverage through use of shorter-wavelength, low-power scanning Doppler radars, as proposed in NRC (2002b)
		900-MHz-band radar wind profilers	150 m to 3-5 km, 60-75 m vertical resolution	*Present arrays:* increase vertical resolution through better signal processing *Future:* add more radar wind profilers, supplement with Doppler sodars *Longer term:* replace with less noisy equivalent
		Doppler sodar	30-200 m at 5-m vertical resolution	Required loud sound pulses make them difficult to deploy; develop radar wind profiler with lower-altitude capability to replace sodar
		MDCRS soundings	Surface-12 km near airports	Availability to C/B/N event forecasters
		Scanning Doppler lidars	*Vert:* 0 to 1-2 km *Horiz:* 10-20 km	Affordable, eye-safe

		Video camera, web camera images of visible plume, flags, etc.	Near surface	Assess current capability (location, visible field, resolution) and then improve as necessary (e.g., install at locations with good visibility)
		Optical crosswind sensors for along street winds (scintillometers)	Across urban canyons	Install in critical areas; need development of a simple inexpensive version of existing systems
	Fill in wind in critical areas	UAVs, mobile scanning Doppler radars, and Doppler lidars	Where sent	Available quickly to critical locations
Depth of turbulent layer(s)	Identify layer(s) through which plume will mix	900-MHz-band radar wind profilers	150 m to 3-5 km	*Present arrays:* increase vertical resolution through better signal processing. *Future:* add more units
		Sodars	30-200 m	Replace with smaller radar wind profiler
Potential for airborne plume to mix to surface	Identify mixing events propagating into area	Scanning lidars	0.1-2 km	Affordable, eye-safe
		Surface tower arrays	2-10 m	As for wind measurements
	Identify potential for mixing event	MDCRS soundings	Surface-12 km	Available to C/B/N forecasters
		Special radiosondes	Surface-30 km	
		RASS	150 m-3 to 5 km	
Winds 500 m and above	Document horizontal transport; model input	400-MHz-band radar wind profilers	Surface-16 km at 300 to 900-m resolution	
		Radiosondes	Surface-12 km	Provision for special radiosonde releases as needed
		Satellite	Where tracers are	Plumes and clouds can be tracked in visible or IR to provide winds; improve satellite wind-tracking capability
Dry deposition	Estimate human, environmental exposure, plume depletion	Data or models used to estimate plume location		
Wet deposition	Estimate human, environmental exposure, plume depletion	Radar, rain gauge, satellites, stream gauges		Merging datasets to get best estimate of rainfall; increased radar coverage; assimilating data into model

[a] GOES stands for Geostationary Operational Environmental Satellite.

surface-mobile platforms for research, and plans should be developed to make such instruments rapidly available for effective, timely use in vulnerable areas.

Local topography and the built environment lead to local wind patterns that can carry contaminants in unexpected directions. Observational networks must represent these local flows as faithfully as possible. Improvements in these networks can be achieved through routine data monitoring and comparison of observed flows with local- to regional-scale model simulations and through numerical modeling, including observing system simulation experiments. Studies should be performed over a range of weather situations and for both day and nighttime conditions. Such exercises will educate meteorologists about local flows and model capabilities; the resulting knowledge of what to believe when observational data and models convey different messages is vital in response to an emergency situation. **Efforts should be made to systematically characterize local-scale windflow patterns (over the full diurnal cycle) in areas deemed to be potential terrorist targets with the goals of optimizing fixed observations and educating those involved in developing dispersion forecasts about local flows and model strengths and weaknesses.**

Focused field exercises are needed to understand the behavior of modeled transport and dispersion in different weather regimes and C/B/N release scenarios, particularly for nocturnal conditions. It is not practical to verify dispersion and transport models for every area with comprehensive field programs, but for an appropriate range of meteorological conditions, physical modeling in a wind tunnel could assist in dispersion model evaluation and threat assessment. In addition, field programs conducted for other purposes, such as improvement of weather forecasting or understanding boundary layer turbulence, also can be useful. **There should be continued field programs focused on C/B/N release issues, and datasets from field programs with a C/B/N or related focus should be made available for testing and development of dispersion and mesoscale transport models.**

Some of the actions recommended above (i.e., enhancing fixed observing arrays, optimizing placement of surface stations and wind profilers, developing and deploying portable scanning lidars, UAVs, and radars) will be costly. **There should be prioritization of such actions based on identifying areas with the greatest need (e.g., highest population concentration, most complex flow, greatest likelihood for a terrorist attack, most vulnerable facilities). Every effort should be made to utilize such instrumentation for other (hazardous and non-hazardous) applications (e.g., to enhance air pollution monitoring, optimize agricultural practices, aid in severe-storm forecasting and highway network safety), thus sharing the costs and ensuring that the array will be continuously used, maintained, and quality controlled.**